IMPLEMENTATION OF FRACTURE CONTROL FOR STRUCTURAL SAFETY OF SPACE FLIGHT SYSTEMS

Michael C. Lou

Jet Propulsion Laboratory, California Institute of Technology, California, U.S.A.

Structural safety is paramount to space flight systems due to the high financial 1OSS and potential damage to national prestige caused by the failure of any space mission. For manned missions, such as NASA's Space Shuttle and Space Station, structural safety becomes even more important for that personnel safety of the flight crew is an added concern.

NASA requires that the implementation of fracture control be an integral part of the structural design and verification process for all payloads to be launched and/or retrieved by the Shuttle, as well as those to be housed and operated in the Space Station. The need to consider structural failures induced by fracture and crack propagation was originated from the well-recognized fact that regardless of the care taken in materials production and parts manufacturing, small cracks and crack-like flaws may be present in flight hardware components, including load-carrying structures. Under cyclic loading of magnitudes over a certain threshold level these flaws will grow. If a flaw is allowed to propagate to a critical size, the growth will become unstable and may cause catastrophic structural failures. Fracture control in the form of damage-tolerance design has long been implemented in the development of commercial and military aircraft structures. However, before the 1970s, the aerospace industry had used fracture mechanics analysis and fracture control methodologies only to verify safe design of space flight pressure vessels and pressurized components. The first large-scale application of fracture control to general, non-pressurized space structures was associated with the development of the Space Shuttle by NASA, The Shuttle development experience showed that, when implemented as an integral part of the overall structural design and verification process, fracture control can significantly improve the safety and reliability of a space system. This led to NASA's decision to require fracture control for all Shuttle payloads.

In the early years of the Shuttle operations, payload fracture control was implemented in a somewhat ad hoc manner, After the Challenger mishap in 1986, NASA went through an extensive safety review of the Shuttle and its operations. As one of the outcomes of the review, formalized requirements and methodologies were developed for systematic implementation of payload fracture control.

This paper presents an overview of NASA's Space Shuttle payload fracture control implementation. It addresses the basic assumptions and limitations, procedures for identifying fracture-critical components, containment and safe-life verification methodologies, capabilities for non-destructive examination inspections, proof test logic, and treatment of inherently safety-critical structural elements, Selected lessons learned from implementation experience of Shuttle payload fracture control over the past sixteen years are also discussed,

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"Michael C. Lou
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

ABSTRACT: Implementation of fracture control for payload structures of NASA manned space flight systems has contributed significantly to the safe operations of the Space Shuttle. An overview of Shuttle payload fracture control program is presented to address the basic assumptions and limitations, procedures for the identification of fracture-critical components, containment and safe-life verification methodologies, capabilities of non-destructive examination inspections, proof test logic, and treatment of inherently safety-critical structural elements. Selected lessons learned from the implementation experience of Shuttle payload fracture control over the past sixteen years are also discussed.

1. INTRODUCTION

Structural safety is paramount to space flight systems due to the high financial loss and potential damage to national prestige caused by failure of any space mission. Structural safety becomes even more important for those space systems associated with manned missions, such as NASA's Space Shuttle and Space Station missions, for that personnel safety of the flight crew is an added concern.

To ensure safety of its manned missions, NASA requires the implementation of fracture control to be an integral part of the structural design and verification process for all payloads that are: (1) to be launched and/or retrieved by the Shuttle, and/or (2) to be housed and operated in the Space Station. The need to consider structural failures induced by fracture and crack propagation was originated from the well-recognized fact that regardless of the care taken in materials production and parts manufacturing, small cracks and crack-like flaws may be present in flight hardware components, including load-carrying structures. Under cyclic loading of magnitudes over a certain threshold level these flaws will grow. If a flaw is allowed to propagate to a critical size, the growth will become unstable and may cause catastrophic structural failures. This concern has long been considered by the aviation industry, For many decades, fracture control in the form of damage-tolerance design has been effectively employed in designing safe structures for commercial and military aircrafts. Fracture-mechanics-based safe-life analysis has also been used in establishing aircraft safety inspection and maintenance schedules. However, before the 1970s, the aerospace industry had used fracture mechanics analysis and fracture control methodologies only to verify safe design of space flight pressure vessels and pressurized components. The first large-scale application of fracture control to general, non-pressurized space structures was associated with the development of the Space Shuttle by NASA. The Shuttle development experience showed that, when implemented as an integral part of the overall structural design and verification process, fracture control can significantly improve the safety and reliability of a space system. This led to NASA's decision to require fracture control for all Shuttle payloads [1].

In the early years of the Shuttle operations, payload fracture control was implemented in a somewhat ad hoc manner, After the Challenger mishap in 1986, NASA went through an extensive safety review of the Shuttle and its operations. As one of the outcomes of the review, the NASA Fracture Control Methodology Panel was fromed and chartered to develop requirements and implementation methodologies and procedures for fracture control of NASA manned space flight systems, including payloads of the Space Shuttle and the Space Station, The Panel completed the development of a set of comprehensive Shuttle payload fracture control requirements and issued them in the document NHB 8071.1 [2], Over the past several years, the Panel has been monitoring and reviewing the implementation of these requirements. Based on the lessons learned, the Panel has recently updated the NHB 8071.1 requirements and, in 1996, reissued them in the document NASA-STD-5003[3]. These requirements are expected to also be applicable to the Space Station payloads that are transported by the Shuttle, However, several structural safety issues and concerns unique to the Space Station, such as long-term exposure to space environment, high-cycle fatigue, meteoroid and debris impacts, etc., need to addressed before the development of comprehensive fracture control requirements for Space Station payloads can be completed.

This paper identifies the role of fracture control in ensuring structural safety of Space Shuttle operations and give an overview of the Shuttle payload fracture control programs. It covers the basic assumption and limitations, procedures for identifying fracture-critical structures, containment and safe-life analysis methodologies, capabilities of NDE inspection techniques, proof testing logic, and treatment of structural elements that are inherently safety-critical. Selected lessons learned from the implementation experience of the Shuttle payload fracture control over the past sixteen years are also discussed,

2. ASSUMPTIONS AND LIMITATIONS

It is the policy of NASA to produce space flight hardware systems with a high degree of structural reliability and safety. This is accomplished by utilizing good engineering practices in the design, analysis, fabrication, inspections, testing, and operations. In keeping with this policy, fracture control is employed to mitigate potential catastrophic failures due to propagation of cracks or crack-like flaws that exit in load-carrying hardware parts. Fracture control is required by NASA for Space Shuttle and Space Station payloads [1], The recently updated NASA requirements for Space Shuttle payloads are given in NASA-STD-5003 [3]. For Space Station payloads, a set of draft fracture control requirements that are closely similar to those for Shuttle payloads can be found in document SSP 30558 [4]. The basic assumptions and limitations that underline these requirements include:

a. All structural elements are assumed to contain one, and only one, critical flaw in the most critical area of the element and in the most unfavorable orientation, the application of non-destructive examination (NDE) to detect but not finding such a flaw does not negate this assumption.

b. The flaw-detection capability of a NDE technique is defined by the upper bound on the size of the detectable flaws, If there are no flaws detected by the NDE technique, this upper-bound size then becomes the smallest initial flaw size that is allowed for any safe-life analysis or test of the structural element,

c. An initial flaw will propagate under cyclic loading at a rate that depends on many factors, including material properties, part geometry, flaw size and shape, operational environments, loading conditions, and magnitude of the loads. When the flaw propagates to a certain size, unstable crack (flaw) growth will occur and may lead to a rupture of the structure.

d. The engineering discipline of linear fracture mechanics provides adequate analysis tools for predicting crack growth and stability in structures of common metals and geometry,

e. The beneficial effects of overload cycles that may retard or arrest the growth of cracks can not be accounted for in a safe-life analysis,

f. A safe-life structure cannot experience, as determined by analysis, unstable crack growth within four service lives, This is to account for the variations of material properties, as well as the uncertainty of flaw detection, load determination and analysis accuracy.

g. From the fracture control standpoint, the service life of a structure starts from its crack-screening by NDE or proof testing and extending through completion of its specified usage. Service life is represented by all significant load cycles and environments encountered by the structure during assembly, handling, testing, transportation, launch and on-orbit operations, and landing.

3. IMPLEMENTATION AND METHOLOGY

Implementation of fracture control for a payload system begins with the development of a fracture control plan by its developing organization. Payload fracture control plans are subjected to the review and approval of an authority designated by NASA. For Shuttle payloads, the approving authority is the STS Payload Safety Review Panel at NASA Johnson Space Center (JSC).

An acceptable fracture control plan must include comprehensive descriptions of: (1) the entity responsible for fracture control implementation and its organization, functions, and authority, (2) hardware design and operations of the payload system, (3) process and criteria to be used for identifying fracture-critical components, (4) fracture control verification methods to be employed, (5) techniques to be used to determine initial flaw sizes, (6) treatment of special equipment and high-safety-risk parts, such as pressure vessels, single-point-failure fasteners, rotating machinery, and composite/bonded structures, and (7) procedures to be used to control material properties, design changes, traceability, and documentation. Of these, items 3 through 6 will be discussed in the following sections, The discussions will be based mainly on the fracture control requirements and implementation approach for Shuttle payloads.

3.1 Identification of fracture-critical structures

A fracture-critical component is one in which the propagation of a pre-existing crack in it may lead to a catastrophic hazard, From the standpoint of Shuttle safety, a catastrophic hazard is defined as an event that can harm or cause fatal personnel injury or loss of the Shuttle. Examples of such an event include a structural failure that releases a mass having sufficiently high kinetic energy to punch a hole through the Shuttle cargo bay wall, a release of a significant amount of hazardous substance into the cargo bay, and a failure that subsequently prevents the closing of the cargo bay door.

For a payload system, the design and use of each of its components must be assessed for fracture criticality and be classified accordingly. To avoid ambiguity, NASA has proposed a standardized fracture control classification process, as defined by the following flow chart:

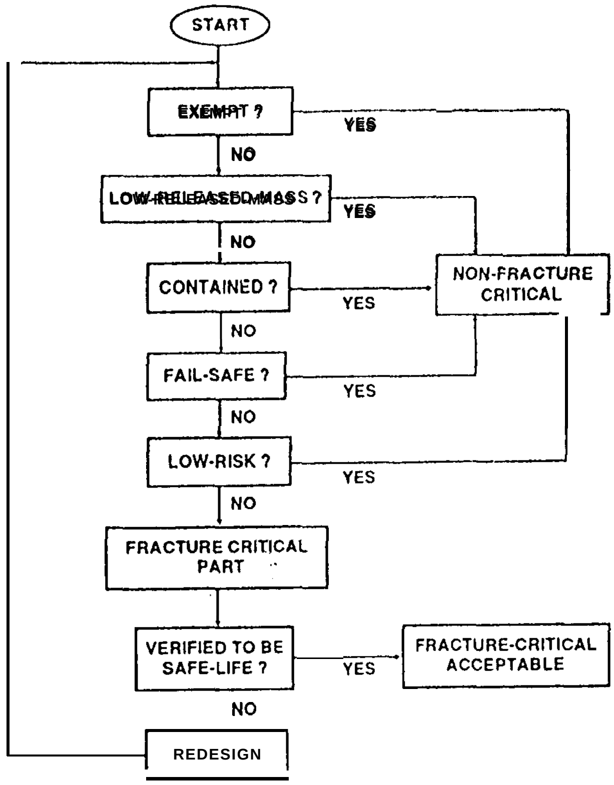

Figure 1. Fracture Control Classification Process

It can be seen in figure 1 that a non-fracture-critical component may fell into one of five categories: (1) exempt, (2) low-released-mass, (3) contained, (4) fail-safe, and (5) low-risk. The criteria for classifying hard ware components into these no-fracture-critical categories are briefly summarized below:

The exempt components are those that are clearly non-structural and not susceptible to failure induced by crack propagation, Some examples of the exempt components are: insulation blankets, wire bundles, and elastomeric seals.

Whether a component can be classified as low-released-mass depends mainly on the total mass it releases after a fracture failure. For parts that are not pre-loaded in tension, the low-released-mass limit is 113.5 grams (0.25 lbs). However, for a pre-tensioned part made of a material having low fracture toughness, such as a titanium bolt, the limit for Iow-released-mass is reduced to only 13.6 grams (0.03 lbs). An additional requirement for a low-released-mass component is that its fracture failure will also not result in a secondary catastrophic event.

A contained component must be contained in such a way that its failure and subsequently the failure of its container does not result in the release of elements with a combined mass exceeding the low-release-mass lim it. The classification of contained components must be supported by documented judgment, analysis, or test, A documented judgment is adequate when obviously satisfactory containment exists, such as closely packed parts in a closed metallic electronics box. To analytically verify satisfactory containment, a number of approximate, as well as rigorous, analysis methods arc available. A common approach is to use the empirically derived "Punch Equation" [5]. This approach assumes that the fragment to be contained has a cylindrical shape with radius R. The minimal thickness, t, of a satisfactory container is calculated by equating the fragment's kinetic energy to the work required to punch out a hole from the container wall. That is:

$$t = \tfrac{1}{2} m^{1/2} (\pi R S_y)^{-1/2} V$$

where m and V are the mass and impact velocity of the fragment, respectively, and S_y is the yield strength of the container wall material. Additional information related to containment design and analysis can be found in [6 and 7].

The fail-safe classification applies mainly to structures of a redundant design. This type of structures, after the occurrence of a single fracture failure, can withstand the re-distributed flight limit loads without releasing into the cargo bay any mass that is over the low-release-mass limit. For example, an electronic box is fail-safe if it is mounted to the spacecraft bus by multiple fasteners. A truss is also fail-safe if there still exists a safe load path after any of its structural elements has experienced a fracture failure. Fail-safe verification of primary load-carrying structures should be accomplished by analysis or test. Analytical verification of structures are in general performed by using standard structural analysis methods and tools (e.g., finite-element modeling). These analyses must account for possible changes in the dynamic characteristics of the residual structure and its post-failure effects on the dynamic loads. For a fail-safe component that is not a primary load-carrying structure, such as the electronics box mentioned above, sound engineering judgment is usually sufficient for its verification.

The low-risk category was recently added to the non-fracture-critical classification to address those highly reliable parts which would otherwise be classified as fracture critical. A low-risk part must be made from a metal known to be highly resistance to fracture and stress-corrosion-cracking. Additional conditions including remote probabilities for the presence of critical crack-like flaws, remote probability of significant crack growth, low stresses, and that its failure will not result directly in a catastrophic hazard, are also applicable to the low-risk classification.

After a component is classified as non-fracture-critical, it can be processed under conventional -strength verification and quality assurance requirements for aerospace structures. On the other hand, any component that fails to be qualified into one of the five non-fracture-critical categories is deemed fracture-critical. A payload system is acceptable to be flown in the Space Shuttle only when all of its fracture-critical components are properly shown, by fracture mechanics analysis and/or test, to have sufficient safe lives in the anticipated operational environment,

3.2 Safe-life analysis

Based on the assumption that a single most critical crack-like flaw exists in any hardware component and grows under cyclic applied loads, a safe-life analysis determines whether this flaw will grow, within four service lives of the component, to a size that can induce unstable growth and cause rupture. Safe-life analysis should be performed based on the state-of-the-art fracture mechanics principles. The payload developers use the appoach derived from the experimentally verified proposition that the rate of growth (da/dN) of a crack is directly related to a single parameter. This parameter, called the stress intensity factor (K), interrelates the flaw size, flaw shape, and geometry of the structure and is defined by:

$$K = \beta(\pi c)^{1/2}\sigma$$

where σ is the applied stress, c is the half length of the crack, and β is a function of the crack size and shape, as well as the structural geometry. When K is equal to Kc , the fracture toughness of the material, an unstable crack-growth leading to a fracture failure occurs.

The performance of stress-intensity-factor-based safe-life analyses follows a crack growth integration scheme that accounts for the initial crack size, the load spectrum describing usage and service life, and the constant-amplitude crack growth rate data. A considerable amount of data is available in the literature on experimentally and analytically derived solutions for stress intensity factors of various structural configurations [e.g., 8, and 9].

Many computer programs capable of performing detailed crack growth analysis are aslo available. The one most widely used by the payload developers is NASGRO. This program was developed and is maintained by NASA JSC under the cognizance of the NASA Fracture Control Methodology Panel. NASGRO employs a highly efficient integration algorithm and contains a library of stress intensity factors for many standard crack configurations, It also maintains a built-in materials database on fracture toughness, crack growth rates and other pertinent mechanical properties. Other features of NASGRO include loads spectra covering standard vibration tests and Shuttle flight, a boundary integral element module for calculating stress intensity factors of non-standard 2-D crack configurations, and improved crack growth rate equations. Additionally, the latest version of NASGRO is also capable of handling life analyses for glass components under sustained stresses. Reference [1 O] is a users manual of NASGRO.

For slow, stable growth of through-the-thickness cracks in structures, the more advanced crack-extension resistance curve (R-curve) approach may be used. R-curves are experimentally determined from laboratory tests of instrumented specimens according to standard ASTM test procedures [11]. Several model equations for fitting R-curve data are described in [1 2].

3.3 Determination of initial crack sizes

For safe-life verification of a fracture-critical component, the size and shape of pre-existing crack-like flaws must be determined, The shape of initial flaws is defined by the ratio, a/c, of the crack depth, a, to the half length of the crack, c. For a safe-life analysis, crack shapes in the range of $0.2<a/c<1.0$ should be considered, However, consideration of the extremes (i.e., a/c = 0.2 and a/c = 1.0) is usually sufficient, Determination of the initial crack size is performed either by a NDE inspection or by proof testing.

NDE techniques commonly employed to determine initial crack sizes in fracture-critical payload structural components are dye penetrant, eddy current, magnetic particle, radiographic, and ultrasonic. The selection of a NDE technique for a specific application depends on many factors, including availability of trained personnel, availability of facility and equipment, material and manufacturing method of the part being inspected, and safe-life requirement of the component. Based on accumulated inspection data and application experience, capabilities of standard NDE inspections, expressed as the smallest detectable cracks at the 90 percent reliability and 95 percent confidence level, are defined in [2 and 3] and summarized in Figure 2. These crack sizes should be used as the minimum initial crack sizes for safe-life analyses of Space Shuttle and Space Station payloads. Crack sizes smaller than those shown in Table 1 are allowed only if the supporting NDE inspection process, i.e., the technique, inspector, and procedures used, has been certified by NASA.

In addition to NDE inspections, proof testing can also be performed to screen initial cracks in structures. The use of proof testing for crack-screening is based on the logic that if a structure survives a proof test without fracture failure, then the knowledge of its fracture toughness and the proof loading allows the bounding of all cracks and crack-like flaws that may exist in the structure. Based on this logic, the maximum size for all cracks that exist in a proof-tested structure cannot be larger than a critical size defined by:

$$c_{cr} = K_C^2/(\beta^2\pi\sigma_p^2)$$

where σ_p is the stress induced by the proof loading. c_{cr} is the maximum initial crack size that should be used for the subsequent safe-life analysis of the structure.

Table 1 Crack-Screening Capability of Standard NDE Infections

Crack Location	Part Thickness, t, mm (in.)	Crack Type	Crack a, mm (in.)	!/2 Crack Length, c, mm (in.)
		Eddy Current		
Open Surface	t ≤ 1.27 (0.050)	Through	t	1.27 (0.050)
	t > 1.27 (0.050)	PTC*	0.51 (0.020) 1.27 (0.050)	2.54 (0.100) 1.27 (0.050)
Edge or Hole	t ≤ 1.91 (0.075)	Through	t	2.54 (0.100)
	t > 1.91 (0,075)	Corner	1,91 (0.075)	1.91 (0.075)
		Dye Penetrant		
Open Surface	t ≤ 1.27 (0.050)	Through	t	2,54 (0.100)
	1.27 (.050)< t < 1.91 (0.075)	Through	t	3.81-t (0.15-t)
	t >1.91 (0.075)	PTC	0.64 (0.025) 1.91 (0.075)	(3.18(0.125) 1.91 (0.075)
Edge or Hole	t ≤ 2.54 (().] ()())	Through	t	2.54 (0.100)
	t > 2.54 (0.100)	Corner	2.54 (0.100)	2.54 (0.100)
		Magnetic Particle		
Open Surface	t ≤1.91 (0.075)	Through	t	3.18 (0.125)
	t > 1.91 (0.075))	PTC	0.97 (0.038) 1.91 (0.075)	4.78 (0.188) 3.18 (0.125)
Edge or Hole	t ≤ 1.91 (0.075)	Through	t	6.35 (0.250)
	t > 1.91 (0.075)	Corner	1.91 (0.075)	6.35 (0.250)
		Radiographic		
Open Surface	0,64 (.025)< t ≤ 2.72 (0.107)	PTC	o.7t	1.91 (0.075)
	t > 2.72 (0.107)	PTC	o.7t	o.7t
		Ultrasonic		
Open Surface	t ≥ 2.54 (0.100)	PTC	0.76 (0.030) 1.65 (0.065)	3.81 (0.150) 1.65 (0.065)

Note: *Partly through crack

Although it is conceptually possible to proof testing all structures, practical constraints limit the type of structures for which proof testing may be an effective crack-screening technique, An important limitation is that the proof test loads must exceed the magnitudes and match the directions of all significant service loads of the structure.

3.4 Fracture consideration of special structural elements

The failure of certain structural elements has inherently high potential to directly cause a catastrophic event. These elements, such as pressure vessels, pressurized lines and fittings, single-point-failure bolts, and high-speed rotating machinery, are fracture-critical by definition and should receive special attention, Of the special fracture-critical elements, pressure vessels are considered the most important for that they usually store a significantly large amount of energy. To mitigate the risk of an explosion, pressure vessels for NASA manned space missions should be designed to be leak-before-burst. The leak-before-burst design criterion requires that pre-existing cracks must grow through the wall of the vessel before becoming unstable, Verification of a leak-before-burst design can be done by analysis or test. For verification of thin-walled pressure vessels that typically have a wall thickness less than 1.5 mm (0.060"), verification can be accomplished by showing that a through-the-thickness crack of a length ten times the wall thickness is stable at the maximum design pressure of the vessel.

Unless a pressure vessel is developed per the American Society of Mechanical Engineers (ASME) boiler codes, which is seldom the case for space flight vessels, it must be designed and verified to MIL-STD- 1522A requirements [13]. This widely used document is currently being updated and converted into an industry standard for space pressure vessels [14] to cover not only metallic pressure vessels, but also composite over-wrapped pressure vessels, Additionally, the inclusion of design and verification requirements for pressurized structures (e.g., main propellant tanks of expendable launch vehicles), pressurized compartments, sealed containers, heat pipes, and cryostat, is also planned for this to-be-published industry standard. It should be noted that for pressure vessels developed for NASA manned missions, certain unique requirements also apply. These include requiring a NDE inspection of welds after proof testing and replacing MEOP (maximum expected operating pressure) with the, usually higher, MDP (maximum design pressure).

A rotating machinery that has a kinetic energy over 19,307 joules (14,240 ft-lbs) is inherently fracture-critical. The rotating components of a fracture-critical machinery that can not meet the the requirements for any non-fracture-critical classification must be proof-tested by spinning and have their safe lives verified,

If the fracture failure of a fastener can cause a direct catastrophic event, it is a single-point-failure fastener and must be classified as a fracture-critical component. A fracture-critical fasteners must be made of a tough alloy, such as A286 steel, that is not susceptible to stress-corrosion-cracking. Fracture-critical fasteners must also meet well-established aerospace quality control specifications and be proof-tested, or NDE inspected, for safe-life verification.

Composite/bonded structures require special attention because they may exhibit more than one failure mode, including fiber breakage, matrix cracking, delamination, and de-bonding. Initial flaws in a composite structure are difficult to detect or define, however, the crack-tip stresses in composite components are less severe than that in metallic parts. Composite structures are also more sensitive to compressive loads and their defects will grow under compression-compression loading.

Fracture control classification of composite/bonded components, like that for metallic parts, follow the same process shown in Figure 1. Once classified as non-fracturee-crtical, a composite/bonded component can be treated just like its metallic counterpart. However, it is generally agreed that safe-life analysis of fracture-critical composite/bonded structures is beyond the current state of the art of linear fracture mechanics. Therefore, fracture control acceptance of these structures is commonly achieved through manufacturing processing control, proof testing, NDE inspections, and/or safe-life testing. NASA accepts a fracture-critical composite/bonded structure for Shuttle flight if it is proof-tested to 1.2 times limit loads. Because composites, when subjected to low-kinetic-energy impacts, may develop delamination not visible on the surface, procedures must also be developed to protect fracture-critical composite structures from accidental impacts during fabrication, assembly, transportation, testing, launch and in-orbit operations.

4. LESSONS LEARNED

Fracture control has been implemented in Space Shuttle payload systems since the early 1980s. Many lessons have been learned from this implementation experience. The following summarize a few of selected lessons learned that can be applied to benefit the development of future payloads for the Shuttle and the Space Station.

1. Fracture control can be cost-effective if it is planned and implemented as an integral part of the payload hardware development program.
2. A great majority of payload hardware can be designed as non-fracture-critical with no or only negligible mass and/or cost penalty. It is important for hardware designers to be aware of pertinent fracture control requirements and classification criteria.
3. Verification of containment and fail-safe classifications of hardware components can usually be achieved by using sound engineering judgment or simple, but conservative, analyses. Rigorous, more accurate analytical verifications are only needed for the most safety-critical structures.
4. Safe-life verification of structures should be accomplished by analysis if possible. Safe-life tests should be avoided because they are difficult, costly, and usually not effective.
5. Safe-life analyses in general need not be performed by a fracture mechanics expert. Because the structural analysts supporting the development of the payload are most familiar with the structural system and have the necessary inputs to safe-life analyses, they should be tasked to perform not only safe-life analyses, but also fracture control classification.
6. The NASGRO crack-growth analysis computer program, as well as its built-in databases of stress intensity factors, material properties, and loads spectrum,

are fully developed and well-maintained. It is prudent for all structural analysts and materials specialists involved with payload development to become familiar with this excellent safe-life verification tool.

7. It is important to remember that there are additional costs and increased development time associated with the required inspection, analysis, traceability, and documentation for every fracture-critical component. The purpose of the "low-risk" non-fracture-critical criterion recently developed by NASA is to help reduce the number of fracture-critical components in a payload without compromising safety. This criterion should be properly used to the maximum extent.

8. The performance of NDE inspection on a non-fracture-critical component should be considered, if: (a) this component is classified as non-fracture-critical based on preliminary, incomplete, or questionable data, or (b) this component, pending possible design changes of its interfacing parts, may become fracture-critical. Once a component is surface-treated and/or assembled, it is more difficult and/or costly to be NDE inspected.

9. For a fail-safe structure designed for multiple missions, in-between-flights inspections are required to ensure that all elements contributing to structural redundancy are intact. If ready access for these inspections is deemed difficult or impossible, it would be sensible to classify the component as fracture-critical and to verify its safe life using a load spectrum covering all expected missions.

10. Fracture-critical components should be made, if possible, of ductile materials having well-defined fracture properties, including toughness and crack growth rate, as well as high stress-corrosion-cracking resistance. In particular, the use of titanium bolts for fracture-critical applications should be avoided.

11. Fracture-critical composite/bonded structures should be designed for ease of proof testing. Protection of these structures against accidental low-energy impacts should be incorporated in the payload handling, transportation, test, and launch procedures,

12. Special attention should be paid to the design and verification of inherently fracture-critical structures early in a payload development program. In particular, metallic pressure vessels should be of a leak-before-burst design and made of materials with sufficiently high toughness for effective proof testing. For composite over-wrapped pressure vessels, damage tolerance and NDE inspection of the liner must be adequately addressed.

5. CONCLUSION

Implementation of payload fracture control has contributed significantly to safe operations of the Space Shuttle. Experience has showed that cost-effective implementation of fracture control can be achieved if it is integrated early into the hardware development processes of a payload ssytem. The effort of NASA to continuously update requirements and to develop improved methodologies and tools also help reduce implementation cost and schedule. The lessons learned over the years from past Shuttle payload programs should be applied to the development of future manned space systems, including the Space Station and its payloads, Focused research and technology development efforts should be initiated to address fracture control issues unique to safe operations of the Space Station, including long-term exposure to space environment, high-cycle fatigue of structures, and effect of meteoroid and debris impacts. The payload developers should follow and contribute to the evolution of Space Station payload fracture control requirements and the development of design and verification requirements for composite over-wrapped pressure vessels.

6. ACKNOWLEDGEMENT

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